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van der Graaff, M.C.W.; Brenner, E.; Smeets, J.B.J.

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RESEARCH ARTICLE

Differences in curvature between constrained and unconstrained goal-directed movements to haptic targets

Marieke C. W. van der Graaff · Eli Brenner · Jeroen B. J. Smeets

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Abstract Trajectories of goal-directed movements are less curved for movements over a surface (constrained) than for movements in empty space (unconstrained). To study whether this difference arises from feeling the surface slip across the skin or having to control the movements in a third dimension, we manipulated the available tactile information and the compliance of the surface. Participants were instructed to make straight movements towards haptic targets in the mid-sagittal plane. We found that constrained movements were less curved than unconstrained movements. The reduction of curvature was also visible with strongly reduced tactile information and for very compliant surfaces, so feeling the surface slip across the skin and having to control the movements in the third dimension are not critical. The reduced curvature when moving over a surface might arise from the extra information that the surface gives about the third dimension or from the extra information about the direction of the movement provided by the additional force needed to overcome friction.

Keywords Goal-directed movements · Movement planning · Haptics · Curvature

Introduction

When we make goal-directed movements, trajectories are generally not straight but slightly curved. It is not clear from the literature when a movement can best be described as curved and when it can best be described as straight. Some authors have called the trajectories of typical goal-directed movements approximately straight (Flash and Hogan 1985; Morasso 1981), while others have called them systematically curved (Papaxanthis et al. 2003; Atkeson and Hollerbach 1985; Brenner et al. 2002; de Graaf et al. 1991; van der Graaff et al. 2014). The trajectories of movements from right to left in a horizontal plane typically have a maximum deviation from a straight line of between 5 and 10 % of the length of the trajectory (Atkeson and Hollerbach 1985; Bergmann Tiest et al. 2011; Brenner et al. 2002; Flanagan and Rao 1995; Helms-Tillery et al. 1994; Miall and Haggard 1995; Osu et al. 1997; Palluel-Germain et al. 2004; Papaxanthis et al. 2003; Prochazka et al. 1978; Rao and Gordon 2001; Uno et al. 1989; de Graaf et al. 1991; van der Graaff et al. 2014). The curvature in movement trajectories depends on the task constraints. For example, it is known that the instruction to move straight reduces the curvature in movement trajectories (Osu et al. 1997; Desmurget et al. 1997, 1999), although the movement trajectories are still systematically curved with this instruction (de Graaf et al. 1991).

Curvature in movement trajectories is also known to depend on the position in the workspace (Atkeson and Hollerbach 1985) and on movement direction (de Graaf et al. 1991; Wolpert et al. 1994). For trajectories with the same start and target location, the curvature is influenced by whether or not one is moving over a surface (Desmurget et al. 1997, 1999): movements over a surface (constrained movements) are less curved than movements in empty space (unconstrained movements). Despite several studies having examined the difference between these two types of movements (reviewed in the next paragraph), it is still unknown why these two types of movements are different.

In a study by Desmurget et al. (1997), participants made both constrained and unconstrained movements towards a

M. C. W. van der Graaff (✉) · E. Brenner · J. B. J. Smeets
MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University, Amsterdam, The Netherlands
e-mail: M.C.W.vander.Graaff@VU.nl

target. With no instruction on how to move, unconstrained movements were more curved than constrained movements (Palluel-Germain et al. 2004; Bongers and Zaal 2010). However, when the instruction was to move straight, there was no difference in curvature between constrained and unconstrained movements. Desmurget et al. suggested that when there is no explicit instruction about the trajectory, constrained movements are planned in the workspace and unconstrained movements are planned in joint space. Bongers et al. (Bongers and Zaal 2010) suggested that when there is no reason to move straight, people may let their hand be pushed towards an easy path.

We were interested in whether we would find less curvature for constrained movements than for unconstrained movements when the task was to move straight. We examined this for movements in the mid-sagittal plane, where some unconstrained movements have been shown to be strongly curved (Atkeson and Hollerbach 1985). If we find effects of constraints on curvature, we could search for their origin. A possible reason for unconstrained movements being more curved even when trying to move straight is that some sources of information that are available for constrained movements are not available for unconstrained movements. One such source of information is tactile information about the direction in which the finger is sliding across the surface. Moreover, the surface provides extra information about the third dimension, and moving over a constrained surface assures that one dimension does not have to be controlled.

In two experiments, we investigate the effect of constraints on movements in the mid-sagittal plane. We investigate whether tactile information and the dimensions in which the arm must be controlled contribute to a smaller curvature in constrained compared to unconstrained movements. In experiment 1, the tactile information is manipulated. If feeling the surface slip across one's finger improves judgments of the direction of motion, manipulating tactile information should influence constrained movements. In experiment 2, the level of compliance of the surface is varied. This alters the extent to which the movement needs to be controlled in the third dimension. In both experiments, we ask participants to move straight to the target.

Method

We performed two experiments that used almost the same methods.

Participants and experimental set-up

This study was part of a program that has been approved by the ethics committee of the faculty of Human Movement Sciences. Eight right-handed participants (mean age 29 years, range 25–40 years) signed an informed consent form before participating in experiment 1. Eight different right-handed participants (mean age 26 years, range 23–29 years) did so for experiment 2. The participants were blindfolded and stood near the edge of a board that was either in their mid-sagittal plane or 40 cm to the left of their mid-sagittal plane (see Fig. 1). On both sides of the board, there were four discs with a height of 1 mm and a diameter of 10 mm, which could serve as start and target locations. In some conditions (unconstrained and fabric), the board was moved 40 cm to the left and four horizontal 40 cm rods, each with a thimble (tip diameter of 13 mm) at its end, were attached to the centres of the discs, (see Fig. 1c, e). In these conditions, the four thimbles were at the same positions as the four discs in the other conditions (constrained and thimble). The height of the board was adjusted so that the participants' noses were always at the same position with respect to the start and target locations. Trajectories were recorded with an OPTOTRAK 3020 system with a sampling frequency of 200 Hz.

Procedure

There were three conditions in experiment 1: *constrained* movements, constrained movements with a *thimble* on the moving finger and *unconstrained* movements. The order of the conditions was varied across participants. On each trial, participants reached with their left index finger towards the goal location of the current trial and kept it there. The left index finger was on the left side of the board for the constrained and thimble condition, and in one of the thimbles in the unconstrained condition. The participants then reached with their right index finger to the start location of the current trial. In the constrained condition, participants had to slide with their right finger over the board (Fig. 1b) to where they felt their finger at the other side of the board. They were instructed to do this by moving in a straight line. Participants were instructed to stop at the place they thought their finger was, and once they had stopped, not to correct if they noticed that they were wrong. In the thimble condition, the task was the same as in the constrained condition, but participants wore a thimble on their right index finger (Fig. 1d). In the unconstrained condition (Fig. 1c), the right index finger started on one of the thimbles, and participants were instructed to move towards their left finger that was placed in one of the other thimbles.

In the unconstrained condition, participants received feedback about errors at the endpoint of their movement when they touched, or did not touch, the thimble with their moving finger, or when they bumped into the thimble with their hand or arm. The discs at the target locations provided similar feedback in the constrained and thimble conditions.

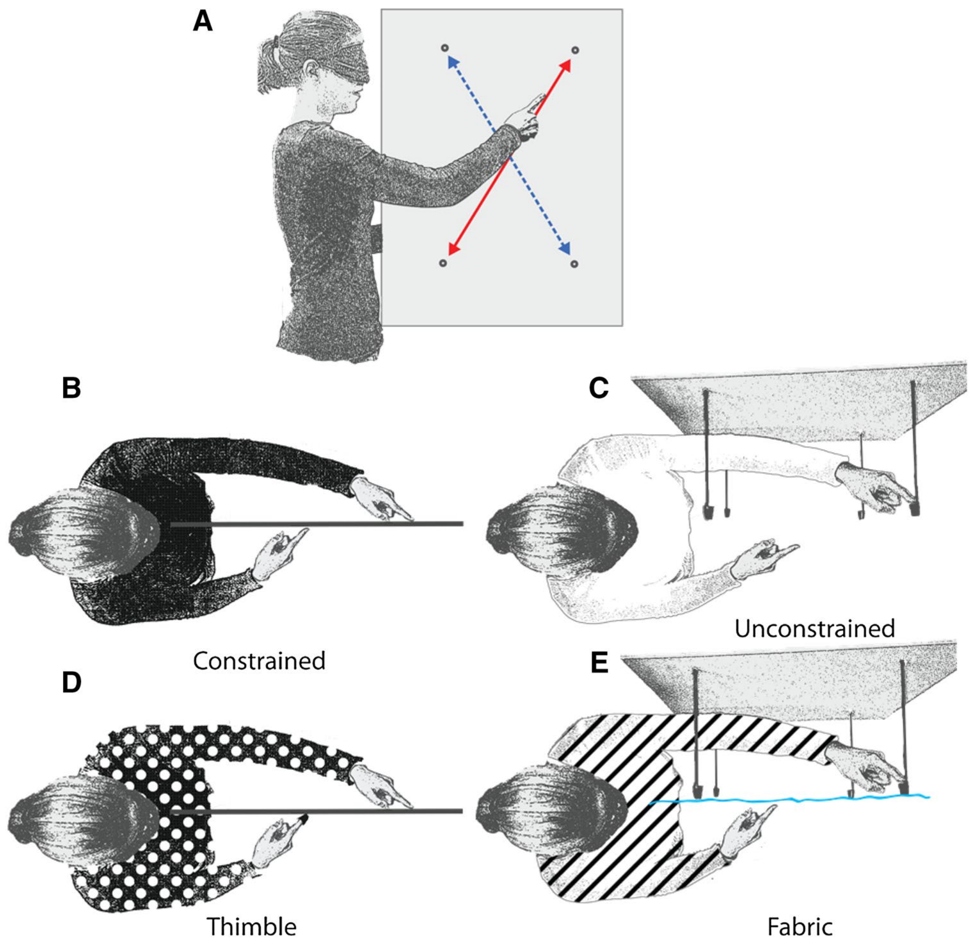

Fig. 1 Side (**a**) and top (**b–e**) views of the experimental set-up. **a** The four paths (pairs of start and target locations) used in the two experiments (*blue dashed*, and *red solid arrows*). **b** Constrained condition without thimble (experiment 1 and 2). **c** Unconstrained condition (experiment 1 and 2). **d** Constrained condition with thimble on the right index finger (experiment 1). **e** (Soft or stiff) fabric condition (experiment 2). The participants only touched the board with their index fingers (colour figure online)

An infrared emitting diode (IRED) was placed on the nail of the index finger of the participant's right hand for recording the movements. In the thimble condition, the IRED was placed on the tip of the thimble.

Experiment 2 was similar to experiment 1; two of the three conditions (*constrained* and *unconstrained*) were repeated, with two new intermediate conditions (*soft and stiff fabric*) so that there were four conditions in total. The intermediate conditions were movements over a stiff and a soft fabric, so that participants moved over surfaces with different levels of compliance. For these conditions, fabric was placed in front of the set-up with the rods (Fig. 1e). The fabrics were attached to a frame that extended about 15 cm around the start and target locations on all sides. The participants started with their right finger on one of the thimbles, which could be felt through the fabric, and moved towards their left finger that was placed in another thimble.

For each of the four combinations of start and target location, the shortest path was 65 cm (Fig. 1a). Based on earlier research (Atkeson and Hollerbach 1985), we expected two of these paths to yield large curvatures (blue dotted line), and the other two to yield small curvature (red solid line). Each path was presented 10 times, giving a total of 40 trials per condition, in random order. The total number of trials per subject was thus 120 in experiment 1 and 160 in experiment 2.

Data analysis

The start and end of the movement were defined on the basis of the movement direction between successive samples (Smeets and Brenner 2004; van der Graaff et al. 2014). If this direction differed by more than 90° from the direction from the starting point to the target, we defined the signal as noise. The transitions between movement and noise were determined by moving backward and forward in time from the moment of peak velocity. These points were defined as the beginning and the end of the movement, respectively. Mean movement times were determined for each participant and condition, and compared between conditions with a repeated measures ANOVA.

The movement plane was defined as the plane in which the movements were made when participants kept contact with the board in the constrained condition. For every trajectory, we determined the projection of the finger's path onto the movement plane and took the maximal deviation from a straight line between the initial and final locations as our measure of curvature (sagittal deviation). Curvature away from the body was defined as positive, so if the sagittal deviation was away from the body, the curvature was considered to be positive, and if it was towards the body, the curvature was considered to be negative on that trial. For each participant, the average sagittal deviation was calculated for every path and condition. A Repeated Measures ANOVA (condition × path) was used to detect consistent curvature in the movement plane across participants. In the fabric conditions and the unconstrained condition, participants could not only curve in the movement plane but also perpendicular to this plane. As a measure for the curvature orthogonal to the movement plane, we used the lateral deviation: the maximal deviation from the movement plane (to the right defined as positive). For experiment 2, a second repeated measures ANOVA (condition × path) was used to compare the mean lateral deviation. Partial Eta squared (η^2) values were calculated as measures of effect size.

Results

Experiment 1

The mean movement times were about 3.3 s, and did not differ significantly between conditions. Figure 2 shows one participant's trajectories. The trajectories are more curved in the unconstrained condition than in the constrained and thimble conditions. Figure 3 shows that this subject was no exception. Overall, the sagittal deviation was larger in the unconstrained condition than in the constrained and thimble conditions. The repeated measures ANOVA revealed an effect of condition [$F(2, 14) = 16.8$, $p < 0.001$, $\eta^2 = 0.71$] and path [$F(3,21) = 3.9$, $p = 0.023$, $\eta^2 = 0.36$], and an interaction between the two [$F(6,42) = 16.9$, $p < 0.001$, $\eta^2 = 0.61$]. Post hoc comparisons (with Bonferroni corrections for three comparisons the p level should be <0.017) revealed that the deviation in the unconstrained condition was larger than that in both the thimble condition ($p = 0.004$) and the constrained condition ($p = 0.003$), and that there was no difference between the constrained and thimble condition ($p = 0.40$). The interaction is significant because this difference is larger for the paths for which more curvature was expected (blue dashed arrows in Figs. 1 and 3). The curvature was systematically larger for these paths for the unconstrained movements. The curvature was consistently away from the body: all mean values are positive.

Experiment 2

The mean movement times were about 3.7 s and did not differ significantly between conditions. The sagittal deviation

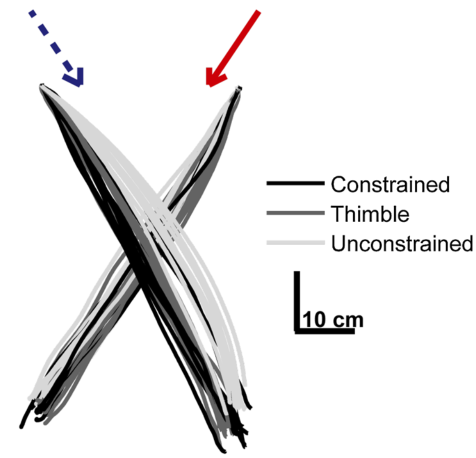

Fig. 2 One participant's trajectories for two of the four paths

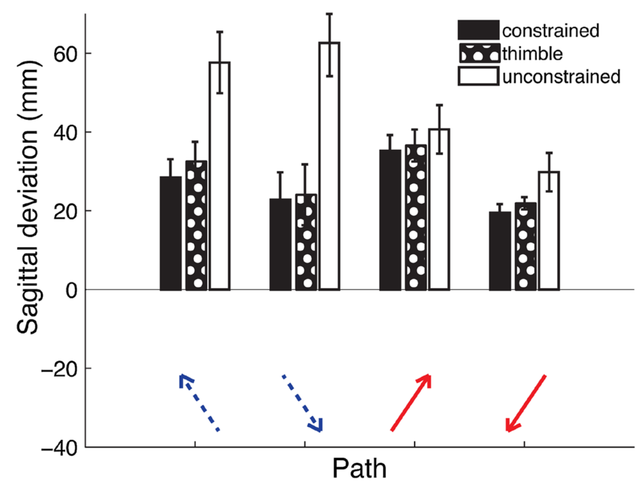

Fig. 3 Mean sagittal deviation for each of the four paths in each of the three conditions of experiment 1. *Error bars* represent the standard error when averaging the means of the eight participants. The *arrows* show the direction of the movement path from the perspective shown in Fig. 1a. A positive deviation is away from the body

was larger in the unconstrained condition than in the other conditions (Fig. 4a). The repeated measures ANOVA revealed an effect of condition [$F(3,21) = 19.1$, $p < 0.001$, $\eta^2 = 0.73$] and an interaction between path and condition [$F(9,63) = 5.1$, $p < 0.001$, $\eta^2 = 0.42$). Post hoc comparisons (with Bonferroni corrections for four comparisons, the p level should be <0.0125) revealed that deviations in the unconstrained condition were larger than deviations in the other three conditions (comparisons with constrained: $p < 0.001$, soft fabric: $p = 0.001$, and stiff fabric: $p = 0.003$). There was no difference between the constrained condition and the two fabric conditions (compared to soft fabric $p = 0.84$; stiff fabric: $p = 0.49$) or between the two fabric conditions ($p = 0.58$). The differences between the unconstrained and the other three conditions were clearest for the

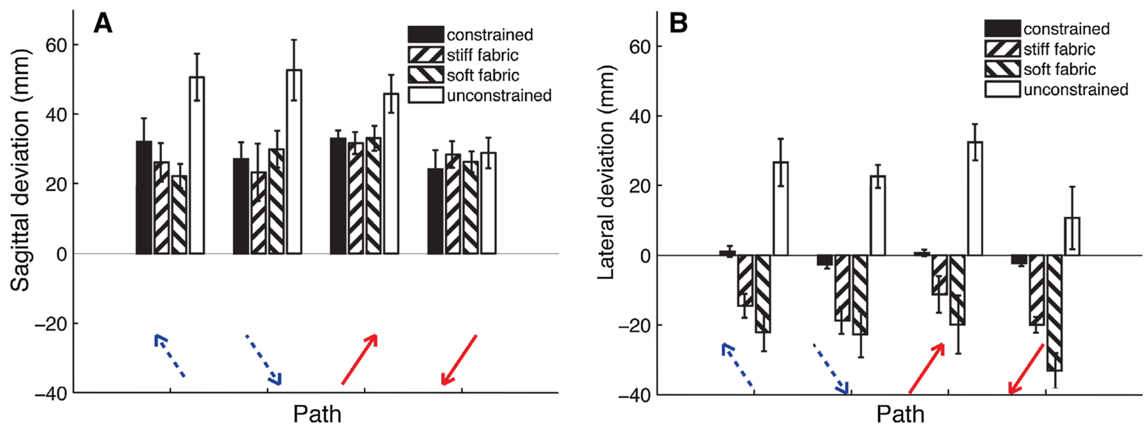

Fig. 4 Results of experiment 2. Mean sagittal (**a**) and lateral (**b**) deviation in each of the four conditions for the four movement paths. *Error bars* represent the standard error when averaging the means of the eight participants. The *arrows* show the direction of the movement path from the perspective shown in Fig. 1a. A positive deviation is away from the body (**a**) or to the right (**b**)

paths for which large curvature was expected (blue dashed arrows), probably giving rise to the interaction effect.

The lateral deviation was to the right for the unconstrained condition and to the left for the two fabric conditions (Fig. 4b). A repeated measures ANOVA revealed an effect of condition [$F(3,21) = 30.4$, $p < 0.001$, $\eta^2 = 0.81$] and path [$F(3, 21) = 5.2$, $p = 0.008$, $\eta^2 = 0.42$]. Post hoc comparisons (with Bonferroni corrections for four comparisons, the p level should be <0.0125) showed that the lateral deviation in the unconstrained condition was different from that in all other conditions (comparisons with constrained: $p = 0.001$, soft fabric: $p < 0.001$, and stiff fabric: $p < 0.001$) and that also the lateral deviation in the constrained condition was different from that in all other conditions (soft fabric: $p = 0.005$, stiff fabric: $p = 0.003$).

Discussion

In this study, we demonstrate that movements between some positions in the sagittal plane are less curved when the movements are constrained (movements over a surface) than when they are unconstrained (movements in free space), even when the task is explicitly to move straight. More importantly, we tried to discover the factors responsible for this. In experiment 1, we compared constrained movements and unconstrained movements with movements that were constrained, but participants wore a thimble on their finger to remove information from feeling the surface slip across the skin of the finger. In experiment 2, we compared unconstrained movements with movements constrained by surfaces with three different levels of compliance. In both experiments, the trajectories in the unconstrained condition were more curved than the trajectories in all other conditions. As we compared paths between precisely the same locations in space, differences in curvature between conditions cannot be explained by gravity or by the biomechanics of the arm.

The two movement paths that were more curved for unconstrained movements than for constrained movements (blue dashed arrows in the figures) were the ones that were most curved in an earlier study (Atkeson and Hollerbach 1985). The high curvature of these movements in the sagittal plane may account for the difference between our results and those of Desmurget et al. (1997), who had subjects move in the horizontal plane.

In the introduction, we mentioned that a possible reason why unconstrained movements are more curved is that tactile information is available for constrained movements but not for unconstrained movements. Touch is known to increase stability when standing (Lackner et al. 2000) and to improve the sense of position (Moberg 1983; Prochazka et al. 1978). When pointing towards a finger with the finger of the other hand without vision of either finger, endpoint errors were reported to be smaller if participants held the fingertip of the reference hand against a surface than if the finger did not touch the surface (Lackner and Dizio 1994; Rao and Gordon 2001; Helms-Tillery et al. 1994). Cutaneous receptors are efficient movement direction and velocity transducers (Gardner and Sklar 1994). For the sense of movement, it is found that both tactile and proprioceptive measures contribute to movement detection (Blanchard et al. 2011; Cordo et al. 2011). In our study (experiment 1), the thimble reduced the tactile information that was available to the participants. In particular, participants could not feel the surface slip across the skin of their finger. This reduction of information did not make the movements more curved, so we can conclude that the absence of tactile information of surface slip is not responsible for the increased curvature in unconstrained movements. It has been shown before that when judging travelled distance, cutaneous information about slip is hardly used (Bergmann Tiest et al. 2011). We show that the same is true for avoiding curvature in movement trajectories.

A second related source of information is the force on the finger when we move over a surface. This force could be divided into two components: the force orthogonal to the surface, and the force that is caused by friction, which is opposite to the direction of motion. The thimble did not eliminate these two forces. Even with the thimble, the participants could feel that they contacted the surface by an orthogonal force and could feel the friction between the sliding thimble and the surface by a force opposite to the direction of motion. In experiment 2, we influenced the orthogonal force by manipulating the compliance of the surface. From the results, we can conclude that the force orthogonal to the surface is not responsible for the differences in curvature in the movement plane. The force orthogonal to the surface is different for the constrained condition and the soft and stiff fabric conditions, but there is no difference in curvature between the movements in these three conditions. The force opposite to the movement direction may be especially important. In a study of Bongers and Zaal (2010), a higher friction reduced curvature. The force opposite to the movement direction has been shown to contribute to haptic curvature judgments (Robles-De-La-Torre and Hayward 2001), while the force orthogonal to the finger has been shown not to contribute much to haptic perception of curvature (Henriques and Soechting 2005), which is in agreement with our interpretations of our results. So the friction force might be one of the information sources that reduce movement curvature.

Another reason why constrained movements could be less curved than unconstrained movements is that a third dimension does not have to be controlled in movements over a constrained surface. When there is more to control, movements might become less precise due to higher muscle activation (more co-contraction), because in isometric force production, precision is proportional to the mean force (Meyer et al. 1988; Schmidt et al. 1979). We found that the different levels of surface compliance did not affect the curvature of the movements. Movements were more curved in the unconstrained condition than in any of the other three conditions in experiment 2. It is therefore unlikely that having to control the movement in the third dimension causes the differences in curvature. The soft fabric moved with the finger when the finger pressed against it, so movement orthogonal to the fabric (lateral deviation) had to be controlled in the soft fabric condition as well as in the unconstrained condition. Nevertheless, the sagittal deviation for the soft fabric was the same as for constrained movements, rather than the same as for the unconstrained movements. So, the absence of control of a third movement-dimension is not the critical factor underlying the reduced curvature in constrained movements.

The soft fabric provided tactile information about the movement plane. Following the fabric assures that in the dimension orthogonal to the fabric, the location of the target is always reached, only uncertainty about the other two dimensions remains. In this case, we indirectly have more information about the location of the target. That movements over the soft fabric condition have the same curvature in the movement plane as ones in the constrained condition suggests that extra information about the target may help to make straighter movements.

In our experiments, participants were blindfolded and made movements towards haptic targets, whereas in other studies (Bongers and Zaal 2010; Desmurget et al. 1997; Palluel-Germain et al. 2004) participants made movements towards visual targets. Although it is known that endpoint accuracy is better when moving towards visual targets than when moving towards haptic targets (van Beers et al. 1998), the curvature in movement trajectories hardly differs (Adamovich et al. 1998; Haggard and Richardson 1996). Movement times were around 3.5 s in our study, whereas they were around 0.5 s in other studies (Bongers and Zaal 2010; Desmurget et al. 1997; Palluel-Germain et al. 2004). Various studies found that movement speed did not influence movement curvature (Nishikawa et al. 1999; Soechting and Lacquaniti 1981), We expect that our conclusions also apply to other movement times and target modalities, because the above-mentioned differences are modest in comparison with our finding that the curvature in unconstrained movements is almost twice as large as the curvature in all other movement conditions, but of course, we cannot be sure of this.

Conclusion

The reduced curvature in constrained movements compared to unconstrained movements probably arises from the additional information about the position of the target in the third dimension that is provided by touching the surface and additional information about the direction in which one is moving along the surface that is provided by forces opposing motion across the surface due to friction.

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